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FATIGUE IN SINGLE CRYSTAL NICKEL SUPERALLOYS
Technical Progress Report

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I. Introduction and Program Objective

This program investigates the seemingly unusual behavior of single crystal airfoil materials. The fatigue initiation processes in single crystal (SC) materials are significantly more complicated and involved than fatigue initiation and subsequent behavior of a (single) macrocrack in conventional, isotropic, materials. To understand these differences it is helpful to review the evolution of high temperature airfoils.

Characteristics of Single Crystal Materials

Modern gas turbine flight propulsion systems employ single crystal materials for turbine airfoil applications because of their superior performance in resisting creep, oxidation, and thermal mechanical fatigue (TMF). These properties have been achieved by composition and alloying, of course, but also by appropriate crystal orientation and associated anisotropy.

Early aeroengine turbine blade and vane materials were conventionally cast, equiaxed alloys, such as IN100 and Rene'80. This changed in the late 1960s with the introduction of directionally-solidified (DS) MAR-M200 + Hf airfoils. The DS process produces a <001> crystallographic orientation, which in superalloys exhibits excellent strain controlled fatigue resistance due to its low elastic modulus. The absence of transverse grain boundaries, a 60% reduction in longitudinal modulus compared with equiaxed grains, and its corresponding improved resistance to thermal fatigue and creep, permitted significant increases in allowable metal temperatures and blade stresses. Still further progress was achieved in the mid-1970s with the development of single crystal airfoils[1].

The first such material, PWA 1480, has a considerably simpler composition than preceding cast nickel blade alloys because, in the absence of grain boundaries, no grain boundary strengthening elements are required. Deleting these grain boundary strengtheners, which are also melting point depressants, increased the incipient melt temperature. This, in turn, allowed nearly complete γ' solutioning during heat treatment and thus a reduction in dendritic segregation. The absence of grain boundaries, the opportunity for full solution heat treatment, and the minimal post-heat treat dendritic segregation, result in significantly improved properties as compared with conventionally cast or directionally solidified alloys. Single crystal castings also share with DS alloys the <001> crystal orientation, along with the benefits of the resulting low modulus in the longitudinal direction.

Pratt & Whitney has developed numerous single crystal materials. Like most, PWA 1480 and PWA 1484 are γ' strengthened cast mono grain nickel superalloys based on the Ni-Cr-Al system. The bulk of the microstructure consists of approximately 60% by volume of cuboidal γ' precipitates in a γ matrix. The precipitate ranges from 0.35 to 0.5 microns and is an ordered Face Centered Cubic (FCC) nickel aluminide compound. The macrostructure of these materials

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[1] Gell, M., D. N. Duhl, and A. F. Giamei, 1980, "The Development of Single Crystal Superalloy Turbine Blades," *Superalloys* 1980, proceedings of the Fourth International Symposium on Superalloys, American Society for Metals, Metals Park, Ohio, pp. 205-214.

is characterized by parallel continuous primary dendrites spanning the casting without interruption in the direction of solidification. Secondary dendrite arms (perpendicular to solidification) define the interdendritic spacing. Solidification for both primary and secondary dendrite arms proceeds in <001> type crystallographic directions. Undissolved eutectic pools and associated microporosity reside throughout the interdendritic areas. These features act as microstuctural discontinuities, and often exert a controlling influence on the fatigue initiation behavior of the alloy. Also, since the eutectics are structurally dissimilar from the surrounding matrix their fracture characteristics will differ.

Single Crystal Fatigue

The fatigue process in single crystal airfoil materials is a remarkably complex and interesting process. In cast single crystal nickel alloys, two basic fracture modes, crystallographic and non-crystallographic, are seen in combination. They occur in varying proportions depending upon temperature and stress state. Crystallographic orientation with respect to applied load also affects the proportion of each and influences the specific crystallographic planes and slip directions involved. Mixed mode fracture is observed under monotonic as well as cyclic conditions.

Single crystal turbine blades are cast such that the radial axis of the component is essentially coincident with the <001> crystallographic direction which is the direction of solidification. Crystallographic fracture is usually seen as either octahedral along multiple (111) planes or under certain circumstances as (001) cleavage along cubic planes.

Non-crystallographic fracture is also observed. Low temperatures favor crystallographic fracture. At higher temperatures, in the 427C range, small amounts of non-crystallographic propagation have the appearance of transgranular fatigue in a related fine grain equiaxed alloy. Under some conditions, this propagation changes almost immediately to the highly crystallographic mode along (111) shear planes, frequently exhibiting prominent striations emanating from the fatigue origin and continuing to failure in overstress. Under other conditions the non-crystallographic behavior can continue until tensile failure occurs. At intermediate temperatures (around 760C) non-crystallographic propagation is more pronounced and may continue until tensile overload along (111) planes occurs, or may transition to subcritical crystallographic propagation. At 982C, propagation is almost entirely noncrystallographic, similar to transgranular propagation in a polycrystal.

Damage Catalogue

This program will identify and compile descriptions of the fracture morphologies observed in SC airfoil materials under various combinations of temperature and stress associated with advanced Navy aeropropulsion systems. We will suggest fatigue mechanisms for these morphologies and catalogue them as unique damage *states*. Most testing will be accomplished under ancillary funding, and therefore be available to this effort at not cost. The work is organized into four tasks, which are described in the following paragraphs.

II. Program Organization

The program is structured into four tasks, three technical and one reporting. The individual tasks are outlined here.

Task 100 - Micromechanical Characterization

This task will define the mechanisms of damage accumulation for the various types of fracture observed in single crystal alloys. These fracture characteristics will be used to establish a series of Damage States which represent the fatigue damage process. The basis for this investigation will be detailed fractographic assessment of failed laboratory specimens generated in concurrent programs. Emphasis will be on specifically identifying the micromechanical damage mechanisms, relating them to a damage state, and determining the conditions required to transition to an alternate state.

Task 200 - Analytical Parameter Development

This task will extend current methods of fatigue and fracture mechanics analysis to account for microstructural complexities inherent in single crystal alloys. This will be accomplished through the development of flexible correlative parameters which can be used to evaluate the crack growth characteristics of a particular damage state. The proposed analyses will consider the finite element and the hybrid Surface-Integral and Finite Element (SAFE) methods to describe the micromechanics of crack propagation.

Task 300 - Probabilistic Modeling

This task will model the accumulation of fatigue damage in single crystal alloys as a Markov process. The probabilities of damage progressing between the damage states defined in Task 100 will be evaluated for input into the Markov model. The relationship between these transition probabilities and fatigue life will then be exploited to establish a model with comprehensive life predictive capabilities.

Task 400 - Reporting

Running concurrently with the analytical portions of the program, this task will inform the Navy Program Manager and Contracting Officer of the technical and fiscal status of the program through R&D status reports.

III. Technical Progress

We have investigated the effects of pernicious environments such as hydrogen. The micromechanics of fatigue and fracture in high pressure hydrogen parallel air behavior in some respects and can provide perspective in the area of Initial Material Quality (IMQ) defect activation. Our interest in defect activation stems primarily from experience with PWA 1480, the current bill of material alloy for the NASA Space Shuttle Main Engine Alternate Turbopump Design (SSME-ATD). This SSME-ATD application includes 1st and 2nd stage turbine blades in both the high pressure fuel and oxidizer turbopumps.

Previously we introduced the concept of a condition dependant defect species; we identified the γ-γ' eutectic as a temperature dependant IMQ defect. The activation mechanism and the resultant fatigue crack initiation mechanism were bulk decohesion from the microstructure at large and subsequent void formation with an associated stress concentration. This mechanism is more akin to that of initiation at a micropore. We have also discussed the concept of a "severity factor" vis-a-vis a particular defect species. An observation that provides an illustrative example of the effect of defect severity (and the concept that LCF behavior is strongly defect driven) follows.

In-situ high pressure hydrogen testing of PWA 1480 at room temperature results in the activation of a normally benign IMQ defect species, the γ-γ' eutectic. The mechanism is by γ-γ' decohesion at the interface between the eutectic lamella, resulting in an extremely (infinitely) sharp microcrack, very different from the pull-out of the entire phase from the microstructure described last month. The severity of this newly described mechanism is extreme when we consider the effect on LCF life. Notched LCF life of PWA 1480 in high pressure hydrogen is reduced by more than an order of magnitude. It can be assumed that since the eutectic composition differs from that of the bulk microstructure a difference in anti phase boundary (APB) energy will exist. We have, in fact, observed the effect of this in the form of phase specific fracture modes (in the eutectic versus the bulk).

Hydrogen is thought to affect the APB energy of both, exacerbating the tendency for dislocation accumulation at the ordered/disorded phase interface resulting in an interfacial fracture. In-situ testing results in very high hydrogen concentrations at the crack tip; once initiation has occurred the bulk microstructure undergoes a similar process (with a 10x increase in fatigue crack growth rate in the hydrogen environment) aggravated by the high stress intensity at the crack tip. The entire fracture is planar, parallel to the $<001>$ direction.

Hydrogen precharging (at 1200°F, 1 hour in 5000 psig hydrogen) and subsequent air testing is another method of evaluating embrittlement. The effects are less severe though, since in air at room temperature hydrogen mobility through the material is minimal. Although high bulk concentrations can be achieved, insufficient concentrations at the crack tip result in lesser effects on fracture mode.

If we precharge in hydrogen but then test in air we see that we have attained sufficient hydrogen concentration to cause the eutectic phase with its already higher APB energy to become a preferential initiator. There is insufficient hydrogen concentration (or mobility at room temperature) in the bulk, however, to incite the bulk microstructure to fail by decohesion so the bulk fracture appears similar to that observed in uncharged material at room temperature, global (111) octahedral crack propagation to failure, the much slower air fatigue crack growth mode.

We have thus demonstrated that although the fatigue crack propagation mechanism following initiation is unchanged from the normal air mode, the initiator has been environmentally activated and the effect on LCF life is identical to that observed when tested in high pressure hydrogen, a 10 - 100x

debit in notched LCF life! This inordinately large life reduction (as compared to hip vs. non hip, for example) we suggest, is primarily an effect of the relative severity of the defect specie (decohesion resulting in a void versus a small crack stemming from interlamellar fracture of the eutectic). To summarize, interlamellar failure of the eutectic is a more severe failure mechanism than pull-out of the eutectic, even though the defect species (the eutectic) is the same for both failures.

IV. Current Problems

No technical problems have been encountered during the reporting period.

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15. Supplementary Notes

16. Abstract (Limit: 200 words)

This program investigates the seemingly unusual behavior of single crystal airfoil materials. The fatigue initiation processes in single crystal (SC) materials are significantly more complicated and involved than fatigue initiation and subsequent behavior of a (single) macrocrack in conventional, isotropic, materials. To understand these differences is the major goal of this project.

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